SCIENTIA
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Testing quality of compression bonding to shearing on six Brazilian hardwood species

Resistência da colagem ao cisalhamento de seis espécies de madeiras tropicais brasileiras

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Abstract

Bonding strength quality tests were conducted on six Brazilian tropical timber species using four types of commercial resins, three PVA bases and one phenol-resorcinol, aiming at their application as structural members and laminated furniture parts. The wood sampling was made at random and conditioned to 12% moisture content at the Forest Products Laboratory (LPF) before bonding. The ASTM D 905-08 (2008) standard was used to bond the timber blocks to a gramature of 300 g/m^2. The species tested were: amapá (*Brosimum parinarioide*), amapá-doce (*Brosimum potabile*), breu sucuruba (*Protium heptaphyllum*), muiratinga (*Maquira sclerophylla*), tauari (*Couratari stellata*), and tacacazeiro (*Sterculia speciosa*). The timbers glued with phenol-resorcinol resin (PR) presented the higher shear strength and wood failure. The resin type A602 produced the strongest bond among those blocks glued with PVA type resins. All wood species laminated and bonded with PR presented higher shear strengths than those of the solid timber.

Keywords: bonding strength; Brazilian tropical timbers; glue line; wood failure.

Resumo

Ensaios de aderência foram realizados em seis espécies de madeiras tropicais brasileiras utilizando quatro tipos de colas comerciais, sendo três à base de PVA (Rhodopas A503, A602 e Extra Performance) e uma a base de resorcinol (Cascophen RS), visando sua aplicação nos laminados colados estruturais e em partes de móveis. A amostragem foi realizada de forma aleatória, conforme metodologia utilizada pelo LPF (Laboratório de Produtos Florestais), condicionadas a 12% de teor de umidade e os blocos de madeira colados segundo a Norma ASTM D 905-08 (2008), com gramatura de 300 g/m^2. As espécies caracterizadas foram: amapá (*Brosimum parinarioide*), amapá-doce (*Brosimum potabile*), breu sucuruba (*Protium heptaphyllum*), muiratinga (*Maquira sclerophylla*), tauari (*Couratari stellata*), and tacacazeiro (*Sterculia speciosa*). As peças coladas com resorcinol apresentaram maior resistência ao cisalhamento e porcentagem de falha na madeira e entre aquelas à base de PVA a cola A602 foi a de melhor desempenho.

Palavras-chave: resistência à colagem; falha na madeira; madeiras tropicais brasileiras.

INTRODUCTION

The use of solid wood in the construction has limitations commonly imposed by its cross section and length. This is significant in members under bending, where there is a need to fill the largest possible spans. This requirement in addition to the characteristic of wood in providing excellent adhesion with synthetic resins was the basis for the creation of glued laminated lumber, which can be used in a variety of structures such as houses, sheds, bridges, boats, etc., with enormous versatility of shapes, cross sections and lengths. It consists basically on bonding timber under pressure up to 50 mm in thickness (depth) in various glue lines. When the joints of the boards are made properly and the glue line is more resistant than solid wood, the structural behavior of laminated lumber is similar to that of the solid piece of wood (PLASTER et al., 2012; NASCIMENTO et al., 2002).

The glued laminated lumber is the result of a practical process for obtaining a high degree of quality control in terms of efficiency of structural wood products. This is made by the possibility of controlling the location of the timber board of different qualities within the beam, according to the requirements imposed by the forces. Thus, the performance of the piece under bending can be maximized by placing the boards of better quality on the top and bottom edges of the beam and in regions with higher demand of stress (CUNHA and MATOS, 2011; MELOTTO, 2007).

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Among the various structural materials used in construction, steel presents shapes and properties that make it more suitable for spanning large lengths in roofs. The glued laminated lumber is an important replacement for steel and can often surpass it in structural efficiency and final cost, depending on the particular characteristics of the project (IWAKIRI et al., 2013).

Most recently the use of wood as engineered material in the construction sector includes applications such as wood I-beam, edge glued panels, glued laminated lumber, laminated veneer lumber, wood framing and others (CUNHA and MATOS, 2011; PATERLINI, 2011). Information about these added value products depend on the research of the bonding quality of the lignocellulosic components. The strength of bonds in web and flanges faces and side joints are important to the overall performance of the structure.

Results of bonding quality of wood from planted forests (mainly *Eucalyptus* sp. and *Pinus* sp.) in Brazil are reported (IWAKIRI et al., 2013; PLASTER et. al, 2012; PLASTER et. al, 2008; LIMA et al., 2008; MELOTTO, 2007; COSTA, 2004; SERPA et al., 2003; NASCIMENTO et al., 2002), however, limited information is available on the bonding resistance of Brazilian tropical species. The Brazilian Amazon region has 3.6 km² and represents 42% of the nation's territory and thousands of species are endemic, but only some one hundred are commercially available (GARCIA et al., 2012). The recent governmental Program of Forest Concessions in the region is currently with some 622 thousand ha under exploitation (SFB, 2013), which may increase the offer of tropical species to the market. The Program has a potential of 308 million ha of public forests already registered, with possibility of managing under concession in the future (SFB, 2013).

A study carried out by Tienne et al. (2008) released the results of wood glued joints of quaruba cedar (*Vochysia* spp.) bonded with resorcinol under different formulations. Nascimento at al. (2013) studied some tropical wood species under two different pressures and gramatures. Some studies show that pressure is not always significant in the bonding shear strength (MACÊDO et al., 2008; NASCIMENTO et al., 2002; MARCATI and DELLA LUCIA, 1996). In Europe information on the bonding quality of some imported Brazilian hardwood species is welcome, as for instance, regarding tauari (*Couratari* spp.), which is used for furniture and wood ladder production.

This work evaluated the strength of adhesion and wood failure at the glue line of six Brazilian hardwood species, with four types of commercial adhesives, three based on PVA (Rodopas A503, A602 and EXTRA) and one phenol-resorcinol (Cascophen RS), intended for the application as the structural glued laminates and furniture bonding.

MATERIAL AND METHODS

The wood species were selected from the density and availability of material from the database of lesser known wood species to the market characterized by the LPF (Forest Products Laboratory), in Brasília, Brazil. These species are reported in the Database of Brazilian Woods, available at <*http://sistemas.florestal.gov.br/madeirasdobrasil*>. In sampling the wood species, the possibility of access in the area of harvesting was considered. Choosing the trees, from harvesting to the preparation of the specimens used in the testing procedures, was performed at random, according to the methodology adopted by the LPF (LISBOA et al., 1993; IBDF, 1988; IBDF, 1981).

The wood species used in the testing are shown in Table 1 with their respective codes.

Table 1. Brazilian wood species and their codes used in the bonding testing.
Tabela 1. Códigos das espécies de madeiras usadas no teste de colagem.

Codes	Wood species	
	Common name	Scientific name
S1	Amapá	*Brosimum parinarioide*
S2	Amapá-doce	*Brosimum potabile*
S3	Breu sucuruba	*Protium heptaphyllum*
S4	Muiratinga	*Maquira sclerophylla*
S5	Tauari	*Couratari stellata*
S6	Tacacazeiro	*Sterculia speciosa*

The four kinds of adhesives chosen for testing were those commercially available and possessing different bonding properties, for instance based on PVA (polyvinyl acetate) and phenol-resorcinol, used for bonding solid and laminated wood members. Table 2 shows the codes used and the characteristics and the assembling variables of the glues.

The bonding of the wood samples was performed following the glue manufacturers' instructions. The glues A503, A602 and EXTRA are PVA bases (white glue), without hardener, manufactured by Rhodia Brasil Ltda. The phenol-resorcinol (PR) glue is an adhesive from Henkel Ltda, with cure at room temperature. It uses a mix ratio of five parts of resin to one part hardener (powder formalin).

Table 2. Glues and codes utilized in the bonding testing.
Tabela 2. Códigos e características das colas usadas no teste de colagem.

Codes	Type of glue	Commercial name	Setting time at 25ºC	Amount of glue
			---- (h) ----	--- (g/m²) ---
G1	PVA - polyvinyl acetate	Rhodopas A503	24	300
G2	PVA - polyvinyl acetate	Rhodopas A602	24	300
G3	PVA - polyvinyl acetate	Rhodopas EXTRA	24	300
G4	Phenol-Resorcinol	Cascophen RS	6	300
Glues characteristics				
G1 - A503	Emulsion Type: polyvinyl acetate polymer Color – Wet: White; Color – Dry: Translucent Viscosity Brookfield RVT, mPa.s (25°C): 6,500 – 8,500 pH (25°C): 4.0 – 5.0 Solids (%): 57.0 – 59.0			
G2 - A602	Emulsion Type: polyvinyl acetate polymer Color – Wet: White; Color – Dry: Translucent Viscosity Brookfield RVT, mPa.s (25°C): 6,000 – 10,000 pH (25°C): 4.0 – 5.0 Solids (%): 50.0 – 52.0			
G3 - EXTRA	Emulsion Type: polyvinyl acetate polymer Color – Wet: White; Color – Dry: Translucent Viscosity Brookfield RVT, mPa.s (25°C): 7,000 – 10,000 pH (25°C): 4.0 – 5.0 Solids (%): 50.0 – 53.0			
G4 - PR	Emulsion Type: Phenol-resorcinol (PR) Color – wet: Reddish; Color – Dry: Reddish Viscosity Brookfield RVT, mPa.s (25°C): 2,127 pH (25°C): 7.3 Solids (%): 61.9			

The wood boards were obtained by use of a circular saw and planed to the nominal sizes of 300x50x20 mm and placed in an air-conditioned environment to reach the equilibrium moisture content of 12%. Blocks were glued in pairs with a gramature of 300 g/m² and pressed to 1.5 MPa. From each block five specimens were cut, according to ASTM D 905-08 (2008). The specimens were again air-conditioned to 12% equilibrium moisture content. Four blocks were bonded per each type of glue, totaling twenty specimens. The samples were tested in shear strength at the glue line and the wood failure was evaluated according to ASTM D 905-08 (2008). The evaluation of the percentage of wood failure at the glue line was carried out as suggested by the European standard EN 314-1 (1993).

The results were analyzed using SPSS version 10.0 plus. The difference among means of shear stress by wood species and type of glue were tested using the Tukey HSD test at 5% significance level. The correlation between load at failure and shear stress was also determined.

RESULTS AND DISCUSSION

The physical and mechanical properties of the wood species were determined at the LPF, according to the Pan American standards (COPANT, 1972), whose test methodology is similar to the U.S. standards ASTM D 143 (1972), and are listed in Tables 3 and 4. The density at 12% moisture content was determined numerically from the basic density and shrinkage, taking the fiber saturation point as 30% of humidity content (MELO, 1988).

Figure 1 shows the results of shear stress at failure. Since the study was outlined in a full factorial, e.g., involving all species of wood glued with all types of glues, the Figure shows the codes of these 24 combinations. For example, the lowest code S2-G3 represents the results of bonding *Brosimum potabile* (code S2) with the A503 resin (code G3).

Table 3. Mechanical properties of the wood species.
Tabela 3. Propriedades mecânicas das espécies de madeiras usadas.

Wood species	Humidity content	Tension at rupture (MPa) [1]				Tension at proportional limit (MPa)	
		Static bending	Compression parallel	Shear parallel	Tension perpend.	Static bending	Compression perp.
Amapá-doce [2]	12%	97.1	55.0	10.2	3.1	10,780	8.2
B. potabile	Green	66.5	31.9	7.4	3.5	8,722	4.0
Amapá	12%	102.2	56.9	10.0	2.9	11,270	8.0
B. parinarioide	Green	67.4	33.6	7.8	3.8	8,820	5.4
Breu sucuruba	12%	85.1	48.0	9.8	5.4	9,800	6.8
P. heptaphyllum	Green	64.3	29.6	7.9	3.3	9,408	4.0
Muiratinga	12%	110.6	60.6	12.0	3.9	11,270	8.4
M. sclerophylla	Green	75.3	36.3	8.7	4.9	10,192	5.5
Tauari	12%	134.0	69.1	12.8	4.5	14,308	11.6
C. stellata	Green	97.0	44.5	9.6	5.3	13,132	8.1
Tacacazeiro	12%	97.0	50.8	9.2	4.0	11,760	5.0
S. speciosa	Green	60.7	27.7	6.2	3.0	9,800	3.5

Source: IBDF (1981), IBDF (1988), Lisboa et al. (1993), SFB (2014).

(1) 1 MPa = 10.205 kgf/cm²; (2) Common/scientific name of the wood species.

Table 4. Physical properties of the wood species characterized.
Tabela 4. Propriedades físicas das espécies de madeiras usadas.

Wood species	Density (kg/m³)			Shrinkage (%)			Tangential/ Radial
	Basic	at 12%	green	Tangential	Radial	Volumetric	
Amapá-doce *Brosimum potabile*	530	639	1130	6.8	4.1	11.9	1.6
Amapá *Brosimum parinarioide*	570	690	1130	7.7	4.5	12.6	1.7
Breu sucuruba *Protium heptaphyllum*	550	666	961	8.4	4.1	12.6	2.0
Muiratinga *Maquira sclerophylla*	570	695	1094	9.4	4.2	13.7	2.2
Tauari *Couratari stellata*	650	792	1130	7.8	5.8	13.4	1.3
Tacacazeiro *Sterculia speciosa*	530	656	1100	11.0	4.8	15.9	2.3

Source: IBDF (1981), IBDF (1988), Lisboa et al. (1993), SFB (2014).

The shear strength ranged from 4.1 to 17.5 MPa. The resin of phenol-resorcinol (G4) conferred the greatest value of shear stress at failure amongst those studied. All species of timber bonded with PR presented values of shear strength superior to those of the solid wood of the same species. In regard to those PVA basis resins, the A602 (G2) was the most resistant and EXTRA (G3) carried the smaller loads to rupture. Three wood species (*B. parinarioide*, *P. heptaphyllum* and *S. speciosa*) bonded with A602 showed shear stress at failure slightly above that of the solid wood. Taking in account only the wood species, there was not a clear tendency to sort resistance, except for the wood of *Couratari stellata*, which showed the best results, yet not statistically different from *Maquira sclerophylla*.

Plaster et al. (2012) using three clones of *E. urophylla* × *E. grandis* originating from three management conditions and density from 620 to 710 kgf/m³ and pressure of 1.2 MPa, obtained shear stress of 10.0 to 14.1 MPa. They used the resins of resorcinol-formaldehyde and PVAc. Tienne et al. (2008) tested glued joints of quaruba cedar (*Vochysia* spp.) with three formulations of phenol-resorcinol and tannin resins in a gramature of 300 g/m² and reported maximum shear stress of 11.1 MPa.

Nascimento et al. (2002) also conducted bonding tests using wood from planted forests (*Pinus taeda*, *P. elliottii* and *Eucalyptus citriodora*) glued with phenol-resorcinol using gramatures of 300 and 600 g/m². The maximum values were 11.8 MPa to *Pinus* and 18.3 MPa to *Eucalyptus*, with a gramature of 300 g/m². According to Nascimento et al. (2002), the wood failure was 90.3% for pine and 25.1% for eucalyptus. The authors also concluded that the gramature of 300 g/m² is satisfactory, which is the same used in this study. The eucalyptus wood used by the authors has a high specific gravity (at 12% moisture content) of 1051 kg/m³. In the present study the wood with the higher specific gravity is *Couratari stellata*, with 792 kg/m³.

Figure 2 shows the values of percentage of wood failure. The glues G1 and G3 had a high percentage of failure in the glue line; the maximum of wood failure was 17%. The glue G2 already shows some values of wood failure in the 90% range, referring to bonding of *Sterculia speciosa*. These types of adhesives are not suitable for use in laminated structural elements. In the case of phenol-resorcinol glue the minimum wood failure was 60% in the gluing of *Protium heptaphyllum*. In other cases, wood failure varied from 83% to 97%, a value satisfactory to the use as structural elements. The Tukey HSD test showed that the glues G1 and G3 presented the lower percentage of wood failure and were not statistically different, followed by the G2 glue, which is inferior to the G4 glue, the most resistant overall.

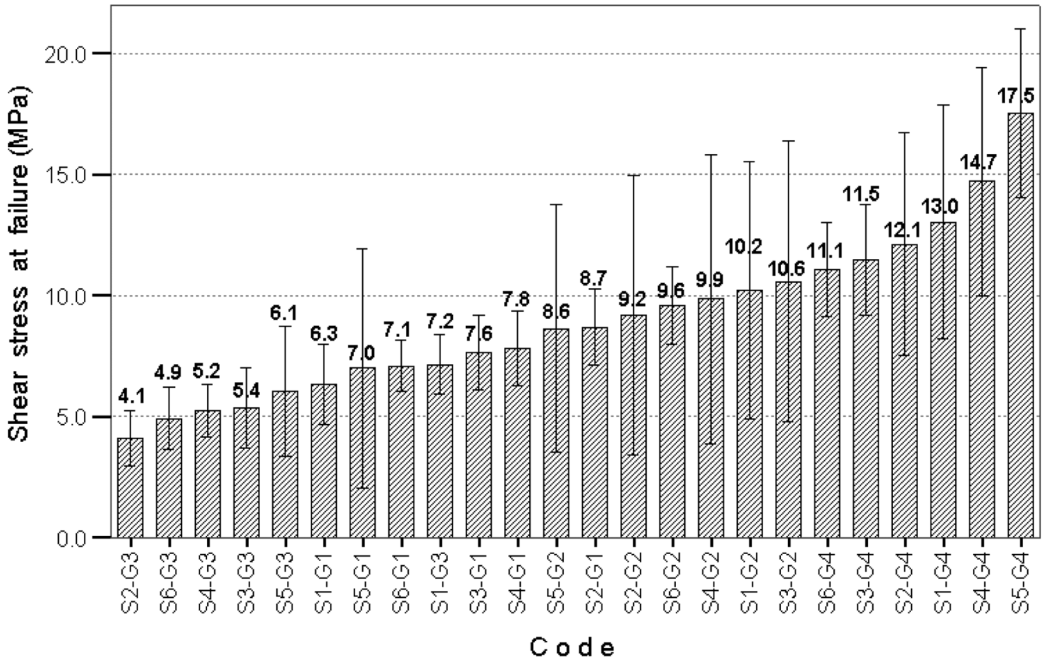

Figure 1. Results of the shear stress at failure of glued wood species by species and type of glue.
Figura 1. Resultados da tensão de cisalhamento das madeiras coladas por espécies e tipos de cola.
Note: S1=Amapá; S2=Amapá-doce; S3=Breu sucuruba; S4=Muiratinga; S5=Tauari; S6=Tacacazeiro; G1= PVA (A503); G2= PVA (A602); G3= PVA (EXTRA); G4= PR (Cascophen RS)

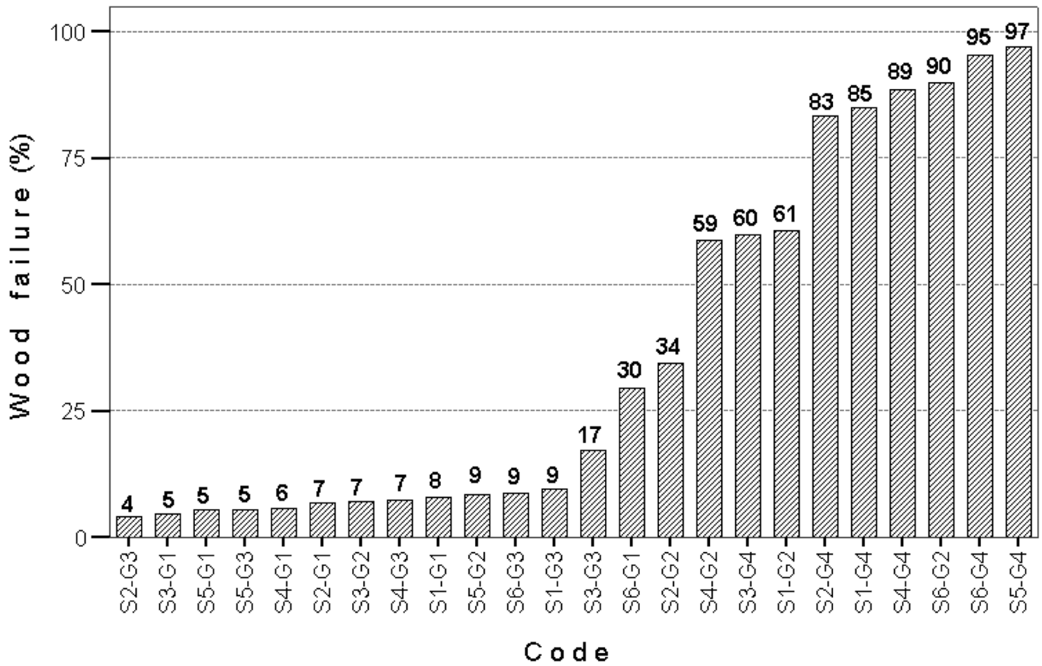

Figure 2. Results of percentage of wood failure by species and type of glue. (Bars and error bars show means and standard deviation, respectively).
Figura 2. Resultados da porcentagem de falha na madeira por espécies e tipos de cola (Barras e linhas em T mostram médias e desvio padrão, respectivamente)
Note: S1=Amapá; S2=Amapá-doce; S3=Breu sucuruba; S4=Muiratinga; S5=Tauari; S6=Tacacazeiro; G1= PVA (A503); G2= PVA (A602); G3= PVA (EXTRA); G4= PR (Cascophen RS).

Figures 3 and 4 show the results of shear stress at failure, by wood species and type of glue. Figure 5 shows the results of maximum loads required to cause the rupture of the bonded samples by wood species and type of glue.

The shear stress at failure and maximum load at rupture were highly correlated, with a coefficient of determination of 0.996 (Fig. 6).

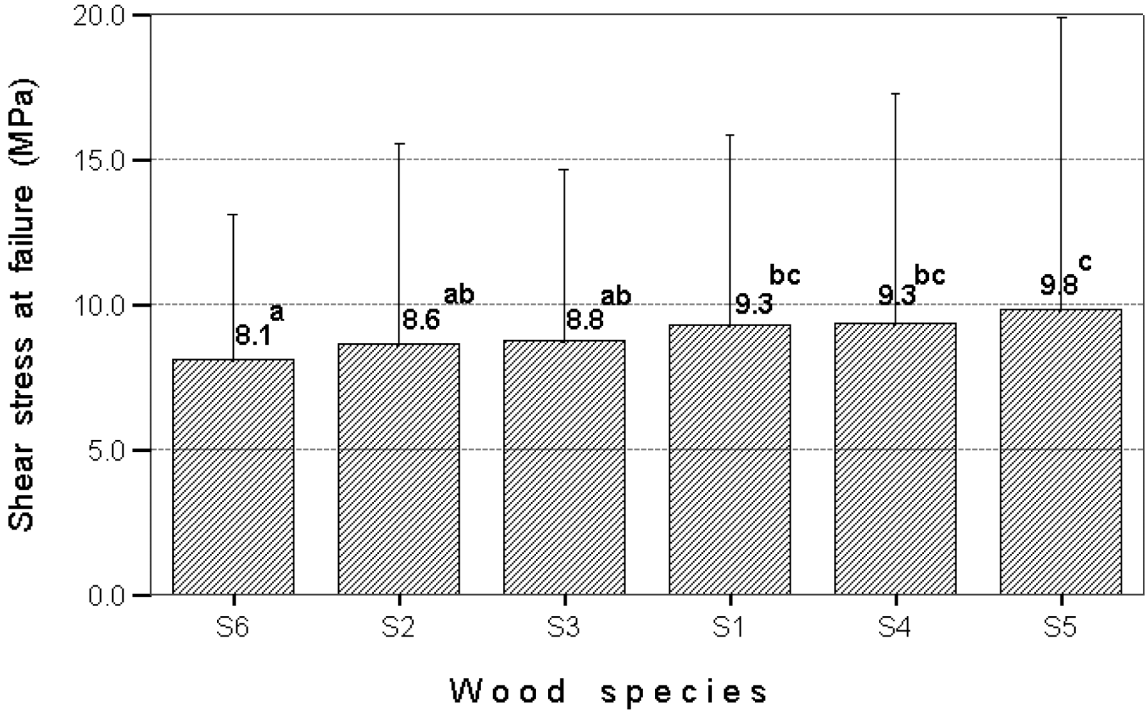

Figure 3. Results of shear stress at failure by wood species. (Bars and error bars show means and standard deviation, respectively). Means with the same letter are not significantly different at 5% significance level.
Figura 3. Resultados da tensão de cisalhamento das madeiras coladas por espécies (Barras e linhas em T mostram médias e desvio padrão, respectivamente). Médias com a mesma letra não são diferentes significativamente ao nível de significância de 5%.
Note: S1=Amapá; S2=Amapá-doce; S3=Breu sucuruba; S4=Muiratinga; S5=Tauari; S6=Tacacazeiro

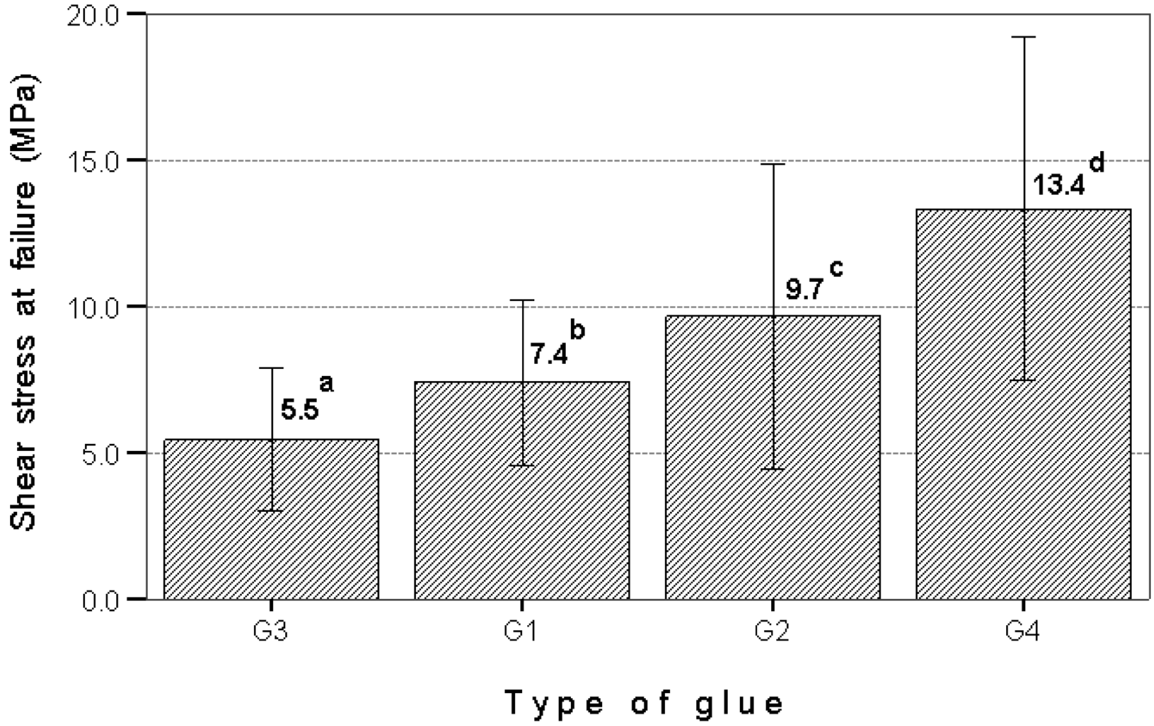

Figure 4. Results of shear stress at failure by type of glue used. Bars and error bars show means and standard deviation, respectively. Means with the same letter are not significantly different at 5% significance level.
Figura 4. Resultados da tensão de cisalhamento das madeiras coladas por tipo de cola (Barras e linhas em T mostram médias e desvio padrão, respectivamente). Médias com a mesma letra não são diferentes significativamente ao nível de significância de 5%.
Note: G1= PVA (A503); G2= PVA (A602); G3= PVA (EXTRA); G4= PR (Cascophen RS)

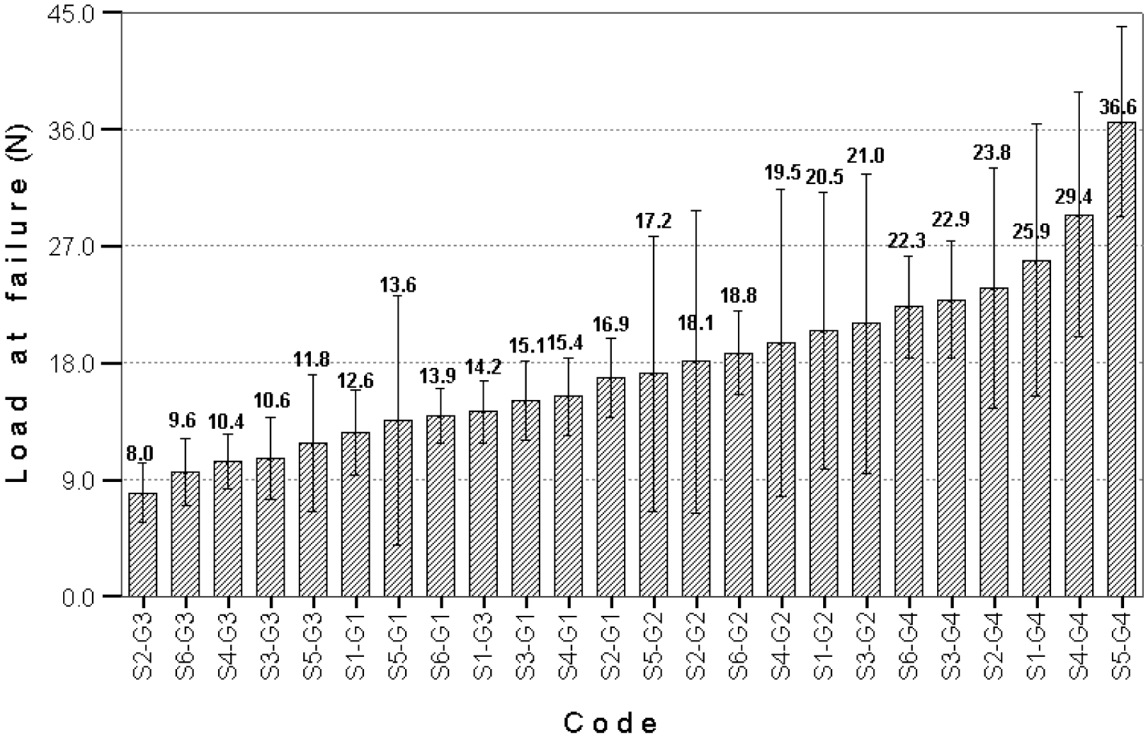

Figure 5. Breaking loads by wood species and type of glue. (Bars and error bars show means and standard deviation, respectively)
Figura 5. Cargas máximas na ruptura por espécies e tipos de cola (Barras e linhas em T mostram médias e desvio padrão, respectivamente).
Note: S1=Amapá; S2=Amapá-doce; S3=Breu sucuruba; S4=Muiratinga; S5=Tauari; S6=Tacacazeiro; G1= PVA (A503); G2= PVA (A602); G3= PVA (EXTRA); G4= PR (Cascophen RS)

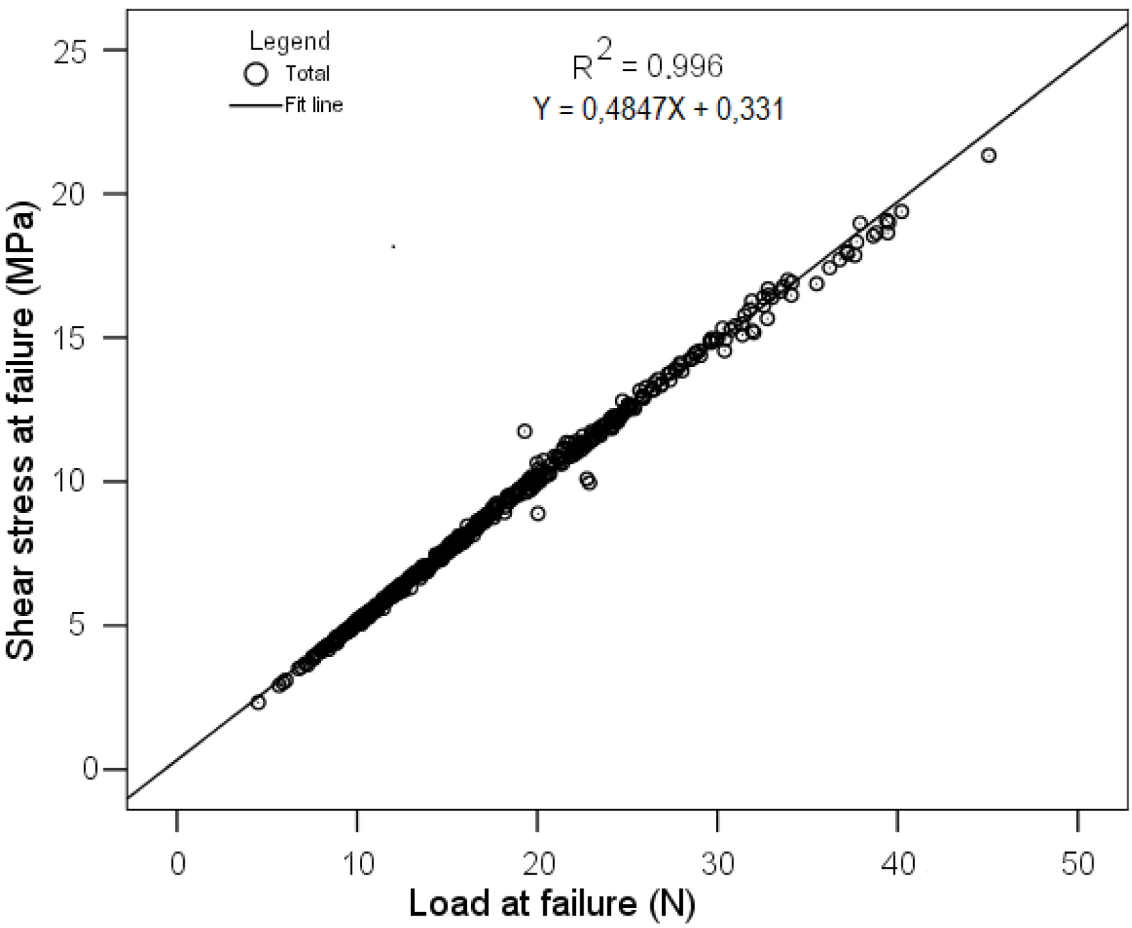

Figure 6. Correlation between shear stress at failure and maximum load at rupture.
Figura 6. Correlação entre tensão de cisalhamento e carga máxima na ruptura.

CONCLUSIONS

The results of bonding quality of the Brazilian tropical wood species studied showed good resistance in bonding with all the glues used, especially *Couratari stellata*.

The phenol-resorcinol resin presented the highest shear strength and is recommended for use as structural laminated parts under high loads. All species bonded with this resin presented shear strength similar or superior to wood from planted forests, such as *Eucalyptus* spp. and *Pinus* spp.

The PVA basis adhesives A602, A503 and EXTRA showed high shear strength, but low percentage of wood failure and are recommended for gluing pieces of furniture. This resin is recommended for interior applications. The phenol-resorcinol is recommended for gluing structural elements and is resistant to humidity.

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